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MATERIALS RESEARCH AND DEVELOPMENT

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**THERMAL-MECHANICAL
TREATMENTS APPLIED TO
ULTRA HIGH STRENGTH
BAINITES**

**First Progress Report
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by

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MATERIALS RESEARCH AND DEVELOPMENT

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ABSTRACT

A program has been initiated to determine the effects of thermal-mechanical treatments on the mechanical properties of high strength bainites. Particular concern will be paid to the strengthening mechanisms involved. The three alloys chosen for study are H11, 4340, and 4350. The pertinent transformation characteristics of these steels are being determined.

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I. INTRODUCTION

Significant improvements in the strengths of low alloy steels have been achieved by the application of mechanical deformation either before or after the formation of martensite. Ausforming; the deformation of metastable austenite prior to transformation to martensite has been shown to develop yield strengths over 300,000 psi in a number of commercial and experimental alloys. In addition, straining and the subsequent aging of as-quenched or tempered martensite also develops exceptionally high strengths in low alloy steels.

Both treatments, ausforming and strain aging have been applied to H11 die steel⁽¹⁻³⁾ and AISI 4340 alloy^(4,5). The reported ductilities and resistance to brittle failure at these improved strength levels have, in general, been equal to or less than that developed by the conventional heat treatment.

High strengths are a desirable but insufficient requirement for most applications. In addition to strength, the ductility and fracture toughness characteristics are also important. In this respect, thermal mechanical treatments involving martensitic structures as the final product do not offer much promise. If strength levels of 300,000 psi or greater are to be used it will be necessary either a) to improve fabrication and inspection techniques so as to eliminate all flaws that could cause premature failure or b) develop materials that possess sufficient ductility and toughness at these ultra-high-strength levels.

In the search for methods to improve the strength, ductility, and fracture toughness of low alloy steels the possible utilization of bainitic structures subjected to thermal-mechanical treatments has been virtually unexplored. This laboratory has obtained a limited indication that significant improvements in the

ductility and strength of H11 can be achieved by combining thermal mechanical treatments with isothermal transformation to a bainitic structure. One process investigated involved deformation of austenite at temperatures in the bay region of the TTT diagram followed by a transformation to bainite, (referred to as ausbainworking). A second treatment examined involves strain aging an ausbainworked structure. The following table compares typical tensile properties of H11 subjected to various treatments:

Table 1
Comparison of Mechanical Properties of Various Treatments

<u>Treatment</u>	<u>0.2% Yield Strength, psi</u>	<u>Ultimate tensile Strength, psi</u>	<u>% elong. in 2 inches</u>
1. Conventional heat treatment	240,000	290,000	5
2. Ausforming	215,000	350,000	5
3. Strain aging martensite	330,000	330,000	2
4. Ausbainworking	250,000	345,000	14
5. Ausbainworking and Strain aging	330,000	346,000	11

It may be seen that the processes involving ausbainworking develop the optimum properties.

This program was initiated to fully evaluate the effect of combining the bainite transformation with thermal-mechanical treatments. The influence of various processing parameters on tensile and fracture toughness characteristics will be determined. Emphasis will be placed upon investigating the strengthening mechanisms and the reasons for improved ductility in H11. In addition, the investigation will be extended to the AISI 43XX class of alloys.

II. EXPERIMENTAL PROCEDURES

A. Materials

The low alloy steels to be studied in this investigation, listed in Table 2, were selected on the basis of the following considerations: (1) the compositions are such that the steels may be deformed as metastable austenite and then transformed to bainite, (2) the tempering behaviors of the alloys in the conventionally heat treated condition are well defined; (3) the influence of thermal-mechanical treatments involving the martensite reaction has previously been studied and (4) the materials are commercially available. Two low alloy steels that meet these requirements are the 5 Cr-Mo-V alloy H11 and the Ni-Cr-Mo alloy 4340. The interesting results from the preliminary investigation of ausbainworking involving H11 suggests that further study of this alloy would be fruitful. A third steel, 4350, was selected for study in order to display the role of carbon content in the various thermal-mechanical treatments. The additional carbon will also provide a lower Ms temperature and thus allow a wider range of bainites to be formed than is possible with 4340. The alloys were obtained as CVM 2' wide sheet in two thicknesses, 0.250" and 0.140". The thicker material will be used for experiments involving deformations of more than 20%.

Table 2
Chemical Compositions

Steel	Element %								
	C	Mn	Si	Cr	Mo	Ni	V	P	S
H11	0.39	0.25	1.00	5.25	1.39	-	0.54	0.011	0.007
4340	0.43	0.68	0.34	0.83	0.24	1.80	-	0.010	0.006
4350	0.52	0.65	0.22	0.88	0.26	1.82	-	0.008	0.006

B. Thermal and Thermal-Mechanical Treatments

The eight basic treatments being employed in this investigation are schematically shown in Figs. 1 and 2.

1. Thermal Treatments

Processes B and M (Fig. 1) refer to the formation of bainite or martensite, respectively, without any deformation being introduced into the heat treatment cycle. Bainite is formed by austenitizing for 30 min. in salt at some temperature (T^A), hot quenching into salt at the appropriate bainite reaction temperature (T^B), holding to the end of transformation (t_f) and oil quenching. Martensite is formed by oil quenching 43XX alloys or air cooling H11 from T^A . Both processes B and M are followed by a double-tempering treatment (1 + 1 hour at T^T) in salt baths. All material is air cooled from the tempering temperatures.

It should be noted that all salt bath temperatures are controlled to within $\pm 5^\circ\text{F}$, while air furnaces are held to $\pm 10^\circ\text{F}$.

2. Deformation of Austenite

Processes AB and AM (Fig. 1) involve the deformation of meta-stable austenite before transformation to either bainite or martensite. Specimens are hot quenched from T^A into a salt bath at the desired deformation temperature (T^D). After 6 minutes in the salt the material is rapidly transferred to an adjacent air furnace for two minutes at the same temperature (T^D) in order to allow the salt to drain and evaporate off. Previous experience in this area has shown that rolling a dry sample from an air furnace is easier than rolling a specimen covered with salt. The specimen is then reduced by rolling in a 2-high 15 inch mill. The reduction in thickness is achieved in 4 passes, with most of the deformation occurring during the first two passes and

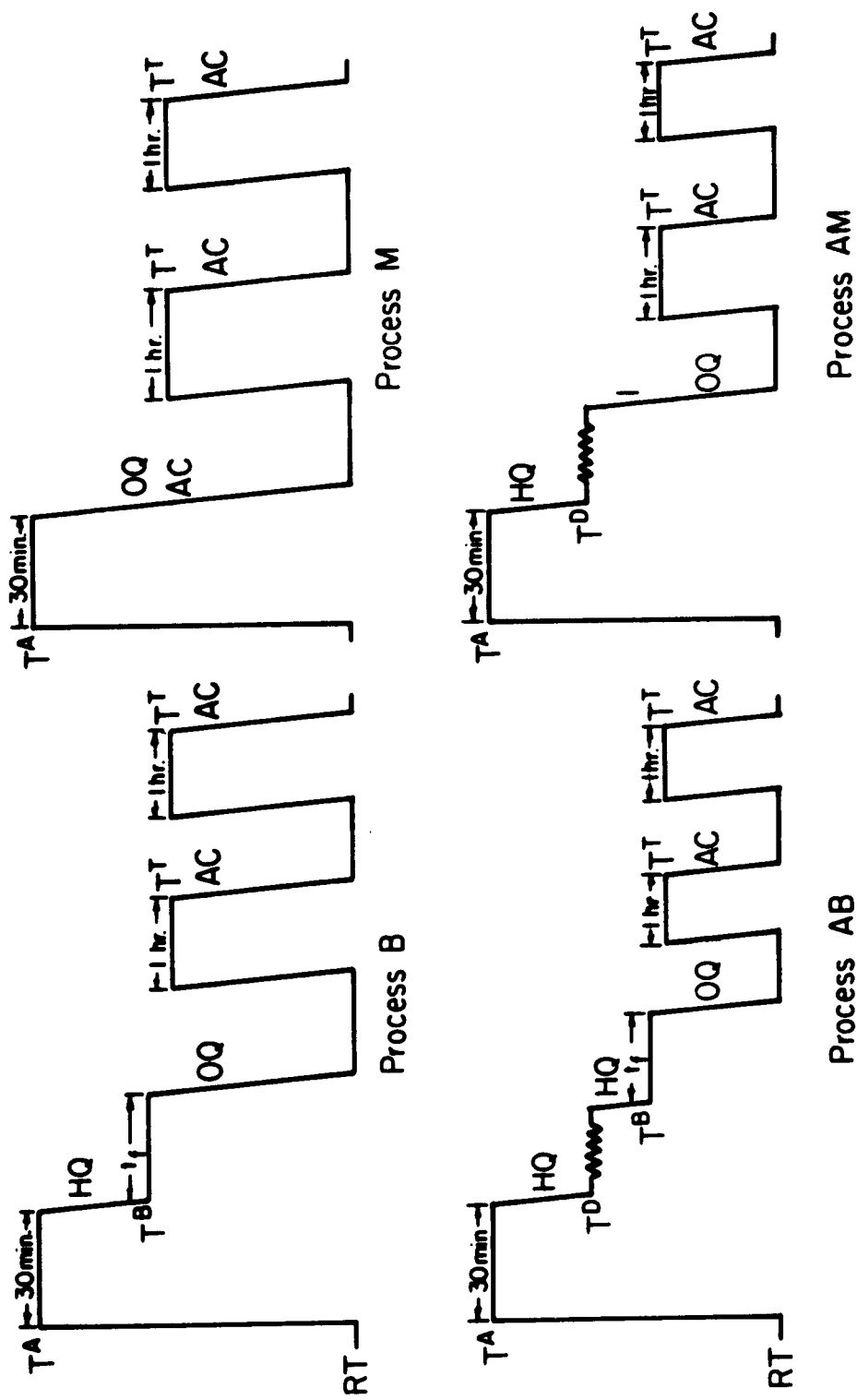


Fig. 1— Schematic Representation of Thermal and Thermal Mechanical Treatments.

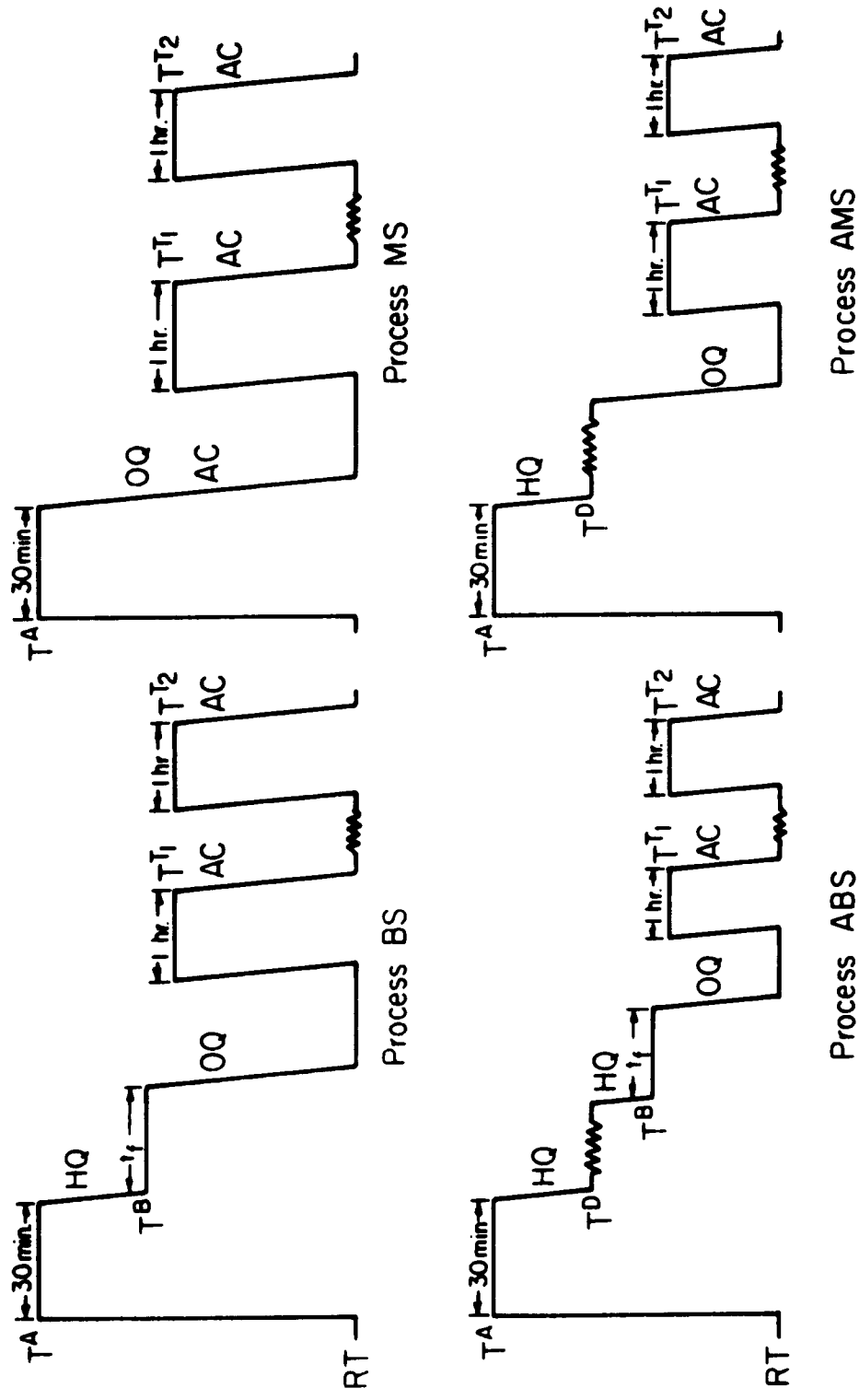


Fig. 2 – Schematic Representation Thermal Mechanical Treatments.

the final two passes used primarily to straighten the blank. Because of a drop in temperature during the rolling operation, specimens are returned to the salt pot (at T^D) for three minutes after each pass and then transferred to the air furnace (at T^D) for two minutes in order to reheat them to the initial deformation temperature. The surface temperature of specimens leaving the rolls, as determined by a contact-pyrometer is approximately 100°F below the temperature of the furnace. The total time at the deformation temperature is twenty-three minutes. The large majority of experiments involving austenite deformation will have a constant percent reduction in thickness of 50%. The 0.250" stock will be used and thus reduced to 0.125". Following the last deformation pass, the specimens will be either hot quenched to T^B in order to form bainite or oil quenched to form martensite. Processes AB and AM will be completed by double-tempering (1 + 1 hour at T^T).

3. Strain-Aging Martensite and Bainite

Processes BS and MS refer to straining bainite and martensite, respectively. After the formation of bainite or martensite the structures are single-tempered (1 hour) at some temperature (T^{T1}). At this point deformation may be introduced at room temperatures either by rolling the original blank or by straining a machined tensile specimen. Although a wider range of reductions can be obtained by rolling, the tension method provides a more homogeneous deformation. These two methods will be compared further in order to select the most desirable method of straining. Following the deformation the structures are retempered (1 hour at T^{T2} , where T^{T1} is not necessarily the same as T^{T2}).

4. Combination Thermal-Mechanical Treatments

Processes ABS and AMS (Fig. 2) combine deformation of the parent austenite phase with straining of the subsequently formed transformation product

(either bainite or martensite). Before these treatments are investigated, the influences of a number of the processing variables on the resulting mechanical properties will be determined for the less complex treatments. As indicated in the data from the preliminary studies of H11, it may be possible to develop desirable properties by combining simple thermal-mechanical treatments.

5. Refrigeration Treatments

For various treatments it will be desirable to introduce subcooling in order to determine the role of retained austenite on the structure and properties. Refrigeration would generally be in liquid nitrogen following: (1) the quench from either T^A , T^D or T^B , depending upon the particular treatment and (2) the first tempering treatment. Particular treatments may also require variations in the subcooling temperature (T^S) in the range between room temperature and liquid nitrogen.

C. Mechanical Testing

1. Hardness and Tensile

The hardness and unnotched tensile properties of the various bainitic and tempered martensitic structures will be determined. The parameters that will be obtained from the tensile test are the yield strength, ultimate tensile strength, elongation and reduction in area.

2. Fracture Toughness

The precracked subsize Charpy test⁽⁶⁾ has been chosen for evaluating fracture toughness. This laboratory has considerable experience in the use of this test; particularly in the field of high-strength steels^(2,3,7). It has been found that this test is highly sensitive, reproducible, economical, and relatively easy to perform and evaluate. The parameter measured will be the energy per unit area, W/A , required to propagate a crack.

The dimensions of the subsize V-notch Charpy specimen will be 2.165 inches in length, 0.394 inches in width and 0.080 inches in thickness. Precracks, about 0.015 inches in length and through the thicknesses, will be produced in a fatigue apparatus developed for this purpose at ManLabs. In order to investigate the effect of strain rate on fracture toughness, both impact and slow bend tests will be performed. Impact or slow bend energy absorption will be measured when necessary as a function of test temperature for various treatments.

The currently most widely selected criterion for fracture toughness in sheet is the critical crack extension force, G_c , obtained from the Irwin-Kies center-notched tensile test. Experimentally, the G_c test is quite difficult to perform, particularly at various temperatures or at impact rates of strain. The specimens are expensive in preparation time and material. Nevertheless, the fact that the results are quantitative and many materials have been evaluated with this test makes it desirable to obtain G_c values for a few conditions of particular interest in this program.

D. Structure Determination

1. Metallography

Light and electron microscopy will be utilized in order to correlate the observed mechanical properties with such microstructural features as prior austenite grain size, carbide and bainite morphology, and volume fraction of the various constituents present.

The times required for the initiation (t_g) and completion (t_f) of the bainite reaction will be established by metallographic examination of isothermally reacted samples. The M_s temperature of each alloy for various austenitizing conditions will be determined by the Greninger-Troiano technique. An accurate

measurement of M_s is essential since bainite reaction temperatures very close to M_s are to be employed.

2. X-Ray

Changes in retained austenite content will be determined by the integrated intensity x-ray technique using monochromatic x-radiation and a scintillation detector. Measurements will be made on the effect of refrigeration and straining on the austenite to martensite transformation.

III. EXPERIMENTAL RESULTS

A. Determination of M_s Temperatures

The martensite start temperatures of the three alloys have been experimentally determined by the Greninger-Troiano metallographic technique. The following M_s temperatures were obtained for the indicated austenitizing temperatures (T^A):

H11 - $M_s = 555^{\circ}\text{F}$	for $T^A = 1850^{\circ}\text{F}$
4340 - $M_s = 590^{\circ}\text{F}$	for $T^A = 1550^{\circ}\text{F}$
4350 - $M_s = 515^{\circ}\text{F}$	for $T^A = 1550^{\circ}\text{F}$

The influence of austenite deformation on the initiation and progress of the martensite reaction is being determined.

B. Bainite Reaction

Hardness specimens have been heat treated in order to determine the progress of the bainite reaction in 4350 and H11. Coupons of 4350 have been austenitized at 1550°F , hot quenched to temperatures in the range of 550 - 900°F , in 50°F intervals, held for times from 1 min. to 12 hours and oil quenched. Blanks of H11 were austenitized at 1850°F , hot quenched to temperatures in the range of 550 - 700°F , in 50°F intervals, held for times from 1 minute to 64 hours and oil quenched. Published transformation diagrams of H11 indicate that: (1) the entire temperature range for bainite reactions is lower than for 43XX type alloys, and (2) no significant degree of isothermal transformation occurs in reasonable times at temperatures above 650°F .

Electron microscopy of selected samples will be employed to determine the type of bainite formed at various reaction temperatures.

C. Limits of Bay Region of TTT Diagram

A particular advantage of H11, with respect to metastable austenite deformation processes, is that the bay region of the TTT Diagram is quite extensive, (700 to 1100°F for times beyond 10^4 minutes). From the literature it appears that the 43XX alloys are not as suitable for such types of thermal-mechanical treatments. Without deformation, the bay region of these steels is limited to temperatures in the range of 950 to 1050°F and is limited to times of the order of 10^2 minutes. In view of these facts the limits of the bay region of 4350 are being accurately determined by hardness and metallography. The effect of deformation on the limits of the bay region is also of particular concern since multipass rolling may be desirable.

IV. FUTURE WORK

The effort in the program will be divided between the following two main objectives: (1) determining the effect of processing variables on resulting mechanical properties for the various thermal and thermal-mechanical treatments and (2) relating structure to properties in an attempt to understand both strengthening mechanisms and the parameters that affect ductility and fracture toughness. Objective (1) will be concentrated upon during the first six months. The treatment variables of interest are given in the following outline:

A. Determine Transformation Characteristics of the Alloys.

1. M_s temperature; with and without austenite deformation.
2. Progress of bainite reaction; with and without austenite deformation.
3. Effect of deformation on limits of bay region of TTT diagram.

B. Processing Variables .

1. Processes B and M (Fig. 1).
 - a. austenitizing temperature (T^A)
 - b. tempering temperature (T^T)
 - c. bainite reaction temperature (T^B)
 - d. degree of transformation
 - e. subcooling temperature (T^S)
2. Processes AB and AM (Fig. 1)
 - a. austenitizing temperature (T^A)
 - b. tempering temperature (T^T)
 - c. bainite reaction temperature (T^B)
 - d. degree of transformation
 - e. subcooling temperature (T^S)
 - f. percent deformation of austenite

3. Processes BS and MS (Fig. 2).
 - a. pretempering temperature (T^{T1})
 - b. retempering temperature (T^{T2})
 - c. percent deformation of martensite or bainite
4. Combination Treatments ABS and AMS (Fig. 2).

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